

Mission Analysis Tool for Turboelectric Powered Unmanned Aircraft Systems

Malorie F. Travis - Author

Oklahoma State University
201 General Academic Building, Stillwater, OK. 74075
malorie.travis@okstate.edu

Abdalrahman K. Mansy - Author

Oklahoma State University
201 General Academic Building, Stillwater, OK. 74075
[mann.mansy@okstate.edu](mailto:mansy.mann@okstate.edu)

Johnathan M. Burgess - Author

Oklahoma State University
201 General Academic Building, Stillwater, OK. 74075
jmburge@okstate.edu

Cole J. Replogle - Author

Oklahoma State University
204 General Academic Building, Stillwater, OK. 74075
coreplo@okstate.edu

Kylar J. Moody - Co-author

Oklahoma State University
201 General Academic Building, Stillwater, OK. 74075
kylar.moody@okstate.edu
ASME Student Member

Kurt P. Rouser - Co-author

Oklahoma State University
201 General Academic Building, Stillwater, OK. 74075

kurt.rouser@okstate.edu

ASME Member

	3
Abstract	3
Introduction	5
Background	6
Hybrid Power Aircraft and Theory	6
Battery Capabilities	7
Model Development	8
Takeoff	10
Constant Speed Climb	11
Cruise and Payload	12
Constant Speed Descent	13
Summary, Conclusions, and Recommendations	14
talk about specific Power here	Error! Bookmark not defined.
Recommended Features and Future Work	14
Acknowledgments	15
Nomenclature	15
Sources	21

Abstract

This paper proposes an analytical model that calculates various flight parameters, such as peak maximum range for pre-determined configurations based on pre-built systems by the research group. The model serves as a tool to compare different turboelectric systems with respect to flight operability and assist in determining an optimal configuration for a select mission flight. This tool performs calculations with user inputs of leg type and altitudes, and battery specifications of capacity, voltage, and discharge rate. Calculations follow basic aerodynamic principles and relations to acquire other flight characteristics such as velocity, fuel burn, and rate of climb.

Introduction

Hybrid power systems are becoming more thoroughly examined for aircraft applications, and as development proceeds, many performance characteristics are unknown. Many mathematical and analytical models have been developed to determine expected efficiencies, power output, and component configuration of various systems, but only a select few exist that model the expected flight operability of hybrid systems. Still fewer models predict turboelectric system operability. Without proper testing, it is unreasonable to compare the range and endurance of traditional power systems, such as piston, turbine, or electric systems, to that of hybrid systems. However, by modeling a hybrid system, the flight qualities may be compared to an extent to traditional systems without the use of physical testing. The applicable proposed hybrid system is a turboshaft engine coupled to a generator, which works with a switching circuit to include electric power from a battery. This system, hereby referred to as the turboelectric system, is likely best used in a full-scale application due to the established benefits that turbine power provides on a large scale. However, the system that will be examined for the purposes of this paper is a subscale Unmanned Aerial System (UAS).

The proposal to address the issue of unknown flight characteristics is a program developed in Python which takes user inputs about the vehicle, fuel, and mission, and it outputs useful calculations for range, endurance, and thrust specific fuel consumption (TSFC). These outputs can then be compared to other configurations to assess overall performance. For example, the tool can be used to compare the range of a configuration with the K-100TP engine with a similar configuration with the K-60TP. This prediction completed by the model is useful in the idea that

it saves the user time and money that would otherwise need to be spent to evaluate the vehicle's flight capabilities.

Background

Aircraft Propulsion Design Process and Relevance of Modeling

While in the process of designing the propulsion systems of various UAS, several steps need to be taken in order to ensure success of the mission and evaluate its performance and usefulness. First, a mission analysis should be performed to identify the design requirements: this step should answer questions such as, "how much thrust is required at each leg?" The next step is to perform a parametric cycle analysis (PCA). The goal of this step is to design the vehicle at a single point in the profile which requires the most power. This is at a single throttle setting with chosen parameters, where the engine is selected. Next, the chosen engine should be evaluated in an engine performance analysis (EPA), where the system will be evaluated over a range of throttle settings and atmospheric conditions in order to verify the engine meets requirements of each leg of the flight. Finally, the mission should be evaluated with the chosen engine to predict flight performance. This step is where this tool comes into use by calculating values such as velocity, power, distance, and flight time as it is accrued during each leg.

Hybrid Power Theory and the Turboelectric Concept

Hybrid powered aircraft and propulsion theories have been around for some time, but the real-world implementation has not been adequately explored. Most systems have the same general configuration, consisting of a gas engine followed by some sort of generator and power conditioning that powers an electric motor and/or charges the onboard battery bank. A turboelectric system is one that takes power produced by a hydrocarbon fuel source, a turboshaft

gas engine, and converts the mechanical power to electric power to drive electric motor and propeller system. In the case of this turboelectric system, the power output from the generator can charge onboard batteries for power augmentation during demanding legs or switching the power source to fully electric during flight.

Both traditional gas and electric power systems offer advantages for UAS, but a turboelectric power system has the potential to use the advantages of each- the high energy density of hydrocarbon fuel and the high-power density of batteries. The turboelectric concept is also scalable to different vehicles, which is useful and adaptable for a range of mission types.

It should be noted that piston engines are commonly used in small aircraft, such as those sized similarly to the Mugin; however, subscale testing of the turboelectric concept may offer advantages over piston engine hybrids because of self-cooling, multiple usable fuel types, and ease of reconfiguration.

Battery Capabilities

The battery type used in the current turboelectric setup is a 12s lithium-ion-polymer battery, 12 Li-Po cells connected in series. This battery was chosen for several reasons, including financial considerations and capability for the desired flight. Metrics used for battery comparisons relevant to this project include chemistry, voltage, capacity, and discharge rate. One of the main reasons for choosing a Li-Po battery is due to its relatively high cell voltage, 3.7-volts, when compared to other battery chemistries. [1]

Batteries are typically chosen by their voltage outputs and discharge capacities. If the propulsive motors have a maximum input voltage of 50-volts, then a 12s Li-Po battery bank would be an optimum choice as its nominal voltage of 44.4-volts. The power demand and flight endurance requirements dictate the discharge capacity necessities of the battery bank. For this reason, a

program that models a hybrid or electrically, powered aircraft can be useful for optimizing battery sizes and power potentials for specific flight requirements. Table 1 shows various battery types and power details relevant to UAS use.

Model Development

To develop a basis for the power requirements of the Mugin 4500mm, an evaluation of the manufacturer's listed specifications was done in Python programming. Estimated coefficients for lift and drag were validated by comparing to values derived from using Mugin's, published takeoff and stall distances [2] in addition with equations for stall velocity and takeoff distance [3].

$$Velocity_{stall} = \sqrt{\frac{2}{\rho_{\infty}} \frac{W}{S_w} \frac{1}{C_{L,max}}} \quad (1)$$

In addition, Mugin supplied the max take-off weight, wingspan, and surface area of the wing. A value of 0.045 was used for the zero-lift drag coefficient of the UAS to account for the added drag of the landing gears. These values and an input for propeller efficiency were used together to determine the thrust and power required of the aircraft throughout a typical flight velocity range. The program also allowed for the user to input the anticipated power available of the aircraft to show as a reference on the power and thrust plots.

Another aspect that the program considers is the distribution of propulsion to three propellers across the airframe. It is assumed that two of the propellers will be mounted at a 45-degree angle from the fuselage to simulate the aircraft's potential short take-off abilities. An optimization is then done to determine best sizes of motors to choose based on a ratio that is input by the user.

The ratio sets the amount of maximum thrust capable of the main rear propulsor as to the thrust capable of the two, smaller, 45-degree oriented propulsors. The initial value is that the

maximum thrust of one of the smaller motors is 75% of the capability of that of the larger motor. It is assumed that the two, angled propulsors produce equal amounts of thrust from one another.

The derived plots and values can be used to validate power requirements for the Mugin 4500 mm aircraft. Another tool that it can be used for is in the sizing and selection of motors for the airplane based on the assumptions stated above.

The proposed turboelectric model was developed in the Python programming language as a tool to meet the needs as specified previously. It was made to be easily navigated by the user, with clear inputs and helpful, graphical outputs. The program graphical user interface (GUI) and a simplified flow chart are shown in Fig. 2 and 3, respectively.

The program takes many desired inputs from the user. For configuration, the user may select between the Mugin UAS with a single aft propeller, the Mugin UAS with the aft propeller and two leading edge propellers, shown in Fig. 4, and the dodecacopter UAS. The engines available are the K-45TP (5 kW), K-60TP (7 kW), and K-100TP (13 kW).

The GUI also takes user input for empty weight, payload weight, and fuel weight. It is important to note that empty weight is not automatically populated by the configuration selection because the selection determined the drag characteristics of the vehicle, but interior components will determine the weight. The battery weight should be included in the empty weight, unless it is intended to be dropped as a payload.

The program allows the user to create a custom mission profile to evaluate a desired systems flight operability. The user has an option from the following legs: takeoff, constant climb, subsonic cruise, payload drop, constant descent, and landing. Calculation of the thrust-specific-fuel-consumption (TSFC) and flight range along each leg requires different assumptions for throttle settings and corresponding fuel burn. General assumptions used for calculations across all legs

include an assumed fuel-to-air ratio, constant electrical and mechanical efficiencies, and a switching circuit configuration. The mission is also assumed to occur at hot day conditions to simulate the worst-case scenario for conservative calculations of TSFC and range. Calculations and methodology for each leg will be discussed in the following sections.

Takeoff

For takeoff roll, an assumed takeoff distance of 50 ft is taken into consideration to simulate the airfield at Oklahoma State University but is arbitrary when comparing the performances of the different systems. In order to calculate the TSFC and fuel burned in takeoff, the thrust required for takeoff is needed. This is calculated with the following equation:

$$T_{TO} = \frac{1.44MTOW^2}{g\rho_{\infty}S_{TO}S_wC_{L,max}} \quad (2)$$

$$F_{TO} = \frac{T_{TO}}{1-\phi_{loss}} \quad (3)$$

The equation considers 25 percent installation losses and an assumed $C_{L,max}$ similar to other aircraft of this nature. The aircraft is assumed to be in full throttle for the duration of the leg, thus the fuel flowrate, \dot{m}_f , is assumed to be at its maximum, a value given by the manufacturer. From this, the flowrate of the air into the engine is calculated:

$$\dot{m}_0 = \frac{\dot{m}_f}{f} \quad (4)$$

Specific-fuel-consumption (SFC) is then calculated, followed by TSFC with the same assumed installation losses.

$$SFC = \frac{f}{F_{TO}/\dot{m}_0} \quad (5)$$

$$TSFC = \frac{SFC}{1-\phi_{loss}} \quad (6)$$

Fuel burned is calculated from the takeoff distance and takeoff velocity, from which we derive the time it the aircraft takes to takeoff from the runway assumed fuel flow. After this, the amount of fuel burned during takeoff is easily calculated, allowing for a more conservative calculation of the flight range of the aircraft.

Constant Speed Climb

The climb calculations are the most complicated of the leg calculations because the rate of climb equation is based on the aircraft weight and in order to calculate the weight of the fuel burned, the time to climb must be calculated, and in order to calculate the time, the rate of climb must be calculated, an endless loop. To simplify the calculation, the weight used in the rate of climb equation will be the weight at the end of takeoff. This assumption should not greatly affect the calculations since the aircraft is a UAS, and the max altitude allowed by the Federal Aviation Administration for UAS is 400 ft, meaning that any practical mission profiles will not greatly exceed this altitude. The time to climb thus should not be too long, so the error of the calculations should not vary greatly from the real values.

For all of the rate of climb leg, the assumption is made that the aircraft will always climb at the maximum rate of climb. For this, the team assumes that the power required for the climbs will be the max power available. From this, the rate of climb at sea level is required in order to integrate the rate of climbs over the different altitudes experienced during the climb.

$$RoC_{SL} = \frac{P_A}{MTOW} - \frac{2}{\rho_{\infty}} \sqrt{\frac{k}{3C_{D,0}}} \sqrt{\frac{MTOW}{S_w}} \frac{1.155}{(L/D)_{max}},$$

and thus the ability to calculate the amount of fuel burned during the climb with the same method used for takeoff. This is done by assuming full throttle and fuel flow. Following this, simple geometry is used to determine the ground distance traveled.

Cruise, Payload Delivery, and Loiter

In order to find the power required by the system at specific speeds, the program follows several aerodynamic equations. First is calculating the drag polar, which is specific to the vehicle and approximated based on size, shape and manufacturer specifications. This can be reasonably accurately approximated given the available data. For a cruise flight, the only forces necessary to overcome is drag, so the required thrust is equal to the drag. This will allow for the TSFC to be calculated. Finally, to get the required power, the required thrust is multiplied by the freestream velocity, or a range of velocities in this case. From this, the time of flight can be determined with an assumed fuel flow. For the sake of cruise, the team assumes that the engine is at $2/3$ throttle, with fuel flow scaled equally. The total cruise range is determined by taking the total amount of cruise legs and equally burning whatever fuel that is expected to not be used for the other legs. This will give the total range of the aircraft for the mission.

The payload leg will be a simple operation where the weight of the payload is simply subtracted from the total aircraft weight. No fuel is assumed to be burned during the payload drop, and this action is assumed to be instantaneous. Although physically the drop will not be instantaneous, it can be modeled as such because it can take place during the leg immediately prior to or aft of the delivery leg.

The loiter leg takes the user's input for altitude and time of loiter. This calculation is also quite simple; the power is assumed to be at two-thirds of the maximum throttle setting, and the fuel burnt is calculated by multiplying the TSFC by the loiter time.

Constant Speed Descent

For descent, the aircraft is assumed to be in a nonpowered, idle setting, and essentially glides to the lower altitude. An arbitrary glide angle is used for all configurations for consistency for all of the calculations.

Landing

The landing distance and velocity are approximated in a simplified way as well. The landing velocity is estimated to be 1.3 times the stall velocity, and the landing distance is the square of the landing velocity divided by g_c .

Summary, Conclusions, and Recommendations

Recommended Features and Future Work

In order for this program to be as useful as possible, several features need to be added or changed. The usefulness of this tool lies mostly in its capability to predict the range and mission time of a hybrid power vehicle, and current functionality only reflects a switching circuit capability, which is without a battery recharge sequence. This is perhaps the most important feature to be added because it would make the tool more relevant and applicable. However, this may be one of the more difficult features to add; in order to add battery recharge capability to the model, fuel flow data is needed in order to approximate a new fuel flow rate during charge. With the added flexibility of battery discharge and recharge functionality, it would be helpful to choose the leg that the user would like to discharge or recharge during. When a power augmentation functionality can be modeled, it would be helpful to model that as well.

As a method of getting the program to run smoothly, we were unable to integrate powered descent into the program. Instead, the program is using a glide approximation for the descent maneuver. This functionality needs to be fixed in order to accurately model the system behavior, power requirements, fuel burn, and subsequently, range.

A relatively small increase in functionality would result from modifying the user inputs to include takeoff details. This would include an obstacle height and, more importantly, roll distance. Another variable would be the surface type; for example, the vehicle could perform the takeoff roll on grass, asphalt, dirt, and more. The surface type would change the coefficient of friction on the roll.

Lastly, the efficiency of the system needs to be physically verified to ensure accuracy of the model. The system from the turbine output to the rectifier output is partially verified, but the remainder of the system is based on estimates for propeller, motor, electronic speed controller (ESC), and wire losses.

References

- [1] Gundlach, J. (2014). *Designing Unmanned Aircraft Systems: A Comprehensive Approach* (2nd ed.). Reston, VA: AAIA.
- [2] Mugin UAV, “Mugin Plus 4500mm Plane Frame Kit,”
<https://www.muginuav.com/product/new-mugin-plus-4500mm-plane/>
- [3] Anderson, J. D. Jr., 1999, *Aircraft Performance and Design*, McGraw-Hill, Boston, MA, p.316

Acknowledgments

The authors would like to thank Dr. Kurt Rouser and Kylar Moody for their assistance and guidance with this project, especially regarding the novel turboelectric concept as a whole and its significance to UAS in the near future.

Nomenclature

TSFC Thrust specific fuel consumption

UAS Unmanned aerial system

D Drag

q Dynamic pressure

S Wing area

CD Coefficient of drag

t_climb time of climb leg

TABLE 1

Battery Type	Theoretical Specific Energy, W-hr/kg	Practical Specific Energy, W-hr/kg	Specific Power, W/kg	Cell Voltage, V
Lead acid (Pb/acid)	170	30–50	180	1.2
Nickel cadmium (NiCd)	240	60	150	1.2
Nickel metal hydride (NiMH)	470	23–85	200–400	0.94–1.2
Lithium ion (Li-Ion)	700	100–135	250–340	3.6
Lithium polymer (Li-Po)	735	50.7–220	200–1900	3.7
Lithium sulfur (LiS)	2550	350	600–700	2.5

FIG. 1

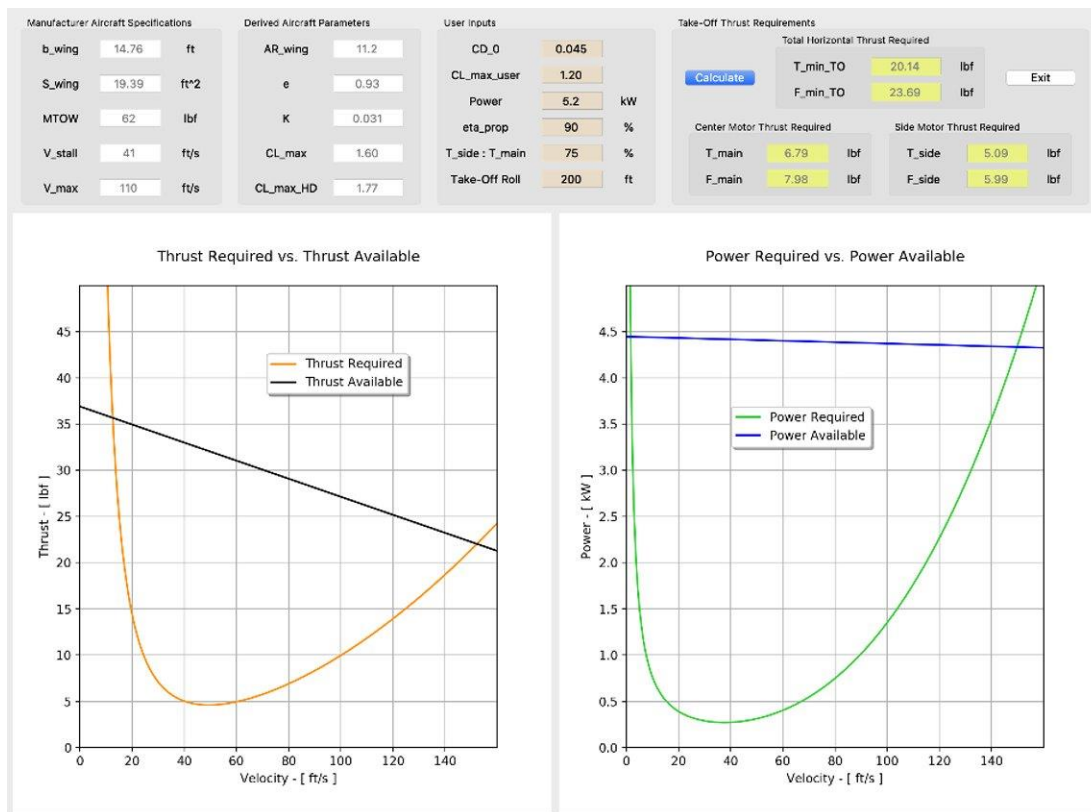


FIG. 2

The image shows a software interface for configuring a mission. It is divided into several sections:

- Configuration:** Contains two dropdown menus. The first is set to "Mugin with 1 propeller" and the second to "K45 - TP".
- Battery:** Contains input fields for "Capacity: 5000 mAh", "Discharge Rate: 60 C", and "Voltage: 44.4 V".
- Aircraft Weights:** Contains input fields for "Empty: [] lbs", "Payload: [] lbs", and "Fuel: [] lbs". A note indicates "(Maximum for Mugin: 13.4 lbs)".
- Mission Leg Details:** Contains a "Mission Leg Type" dropdown set to "Takeoff rol", and "Altitude" fields for "Start [] ft" and "Finish [] ft". There is an "Add Leg" button.
- Current Mission Profile:** Contains a large empty rectangular area and a "Run!" button.
- Output Report / Mission Profile:** A large area at the bottom with two tabs: "Output Report" (selected) and "Mission Profile".
- Exit:** A blue button at the bottom center.

FIG. 3

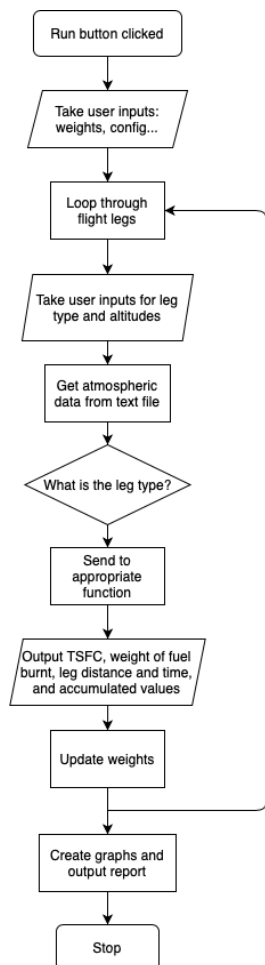


FIG. 4

